MACHINE PARAMETER STUDIES FOR AN FEL FACILITY USING STAFF*

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Abstract

Designing an FEL facility requires balancing multiple science needs, FEL and accelerator physics constraints, and engineering limitations. STAFF (System Trade Analysis for an FEL Facility) is a MATLAB program that enables the user to rapidly explore a large range of Linac and FEL design options to meet science requirements. The code uses analytical models such as the Ming Xie formulas when appropriate and look-up tables when necessary to maintain speed and flexibility. STAFF's modular design simplifies the inclusion of new physics models for FEL harmonics, wake fields, cavity higher-order modes and aspects of linac design such as the optimization of a laser heater, harmonic linearizer, and one or more bunch compressors. Code for the microbunching instability has been included as well. STAFF also supports multiple undulator technologies. STAFF permits the user to study error tolerances and multiple beamlines so as to explore the full capabilities of an entire user facility. This makes it possible to optimize the integrated system in terms of performance metrics such as photons/pulse, photons/sec and tunability range.

INTRODUCTION

The goals of the system trade analysis are to (1) optimize the integrated system performance of an X-ray FEL Facility, (2) predict photons/pulse, photons/sec, and tunability range for a wide range of system parameters, (3) evaluate optimization of the linac for multiple beamline facilities, (4) allow for performance metrics that can include both X-ray production and other project considerations, and (5) help guide R&D priorities and facilitate thinking about performance vs. risk. The tool is for parameter surveys; full simulations can confirm and explore specific design points.

The code must be able to evaluate thousands of cases rapidly, using analytic relationships when available. These relationships include the Ming Xie formulas, emittance and energy spread scaling with bunch charge from photo-injector operational experience, and wiggler technology limits from the magnet groups. Many scaling laws are implemented in STAFF, although some require further validation and verification. The scaling laws include harmonic generation, wake fields, higher-order modes, seeded FEL power requirements (for various schemes), linac particle dynamics (e.g. microbunching), wiggler particle dynamics, accelerator cell performance, and injector performance. Many effects are in the process of being implemented. These include error tolerances, approximate radiation damage, and image current heating for SC wigglers. In some cases it will be necessary to use table-lookup or a best fit to simulations.

SPECIFIC MODULES FOR LINAC AND FEL MODELING

STAFF is structured so as to contain individual modules for different parts of the machine. In this section, we describe the modules contained in STAFF. Beyond doing numerical calculations, the modules can also issue "warning flags" to the main framework. For example, the undulator module can issue a warning flag if the required undulator parameter is not achievable with the selected undulator technology.

Module for the superconducting RF linac

The module for the superconducting RF linac begins its calculation by preparing an ensemble of cavities with a distribution of parameters. This ensemble can be set up with gradient setpoints according to the process described in Ref. [1], and the needed refrigeration capacity can then be computed.

Module for emittance scaling

The emittance scaling module calculates the emittance from the bunch charge, based on studies of this dependence. The longitudinal emittance is chosen to scale as the 0.65 power of the total bunch charge. while the transverse emittance is chosen to scale as the 0.3 power of the total bunch charge.

Undulator module

The undulator module uses scaling laws that give the peak magnetic field as a function of the magnetic gap and the undulator period. For the case of Hybrid Permanent Magnet technology, it is currently just a function of the ratio x=gap/period. Under the assumption that the ratio x is less than unity but not too small, the scaling law is

$$\begin{aligned} B_{\text{peak}} &= 3.25\, B_r \exp\left(-5.08\, x + 1.54\, x^2\right) \\ &= 4.22\, T\, \exp\left(-5.08\, x + 1.54\, x^2\right). \qquad (1) \end{aligned}$$

Based on data for $Nb_3\, Sn$ undulator technology [7], we

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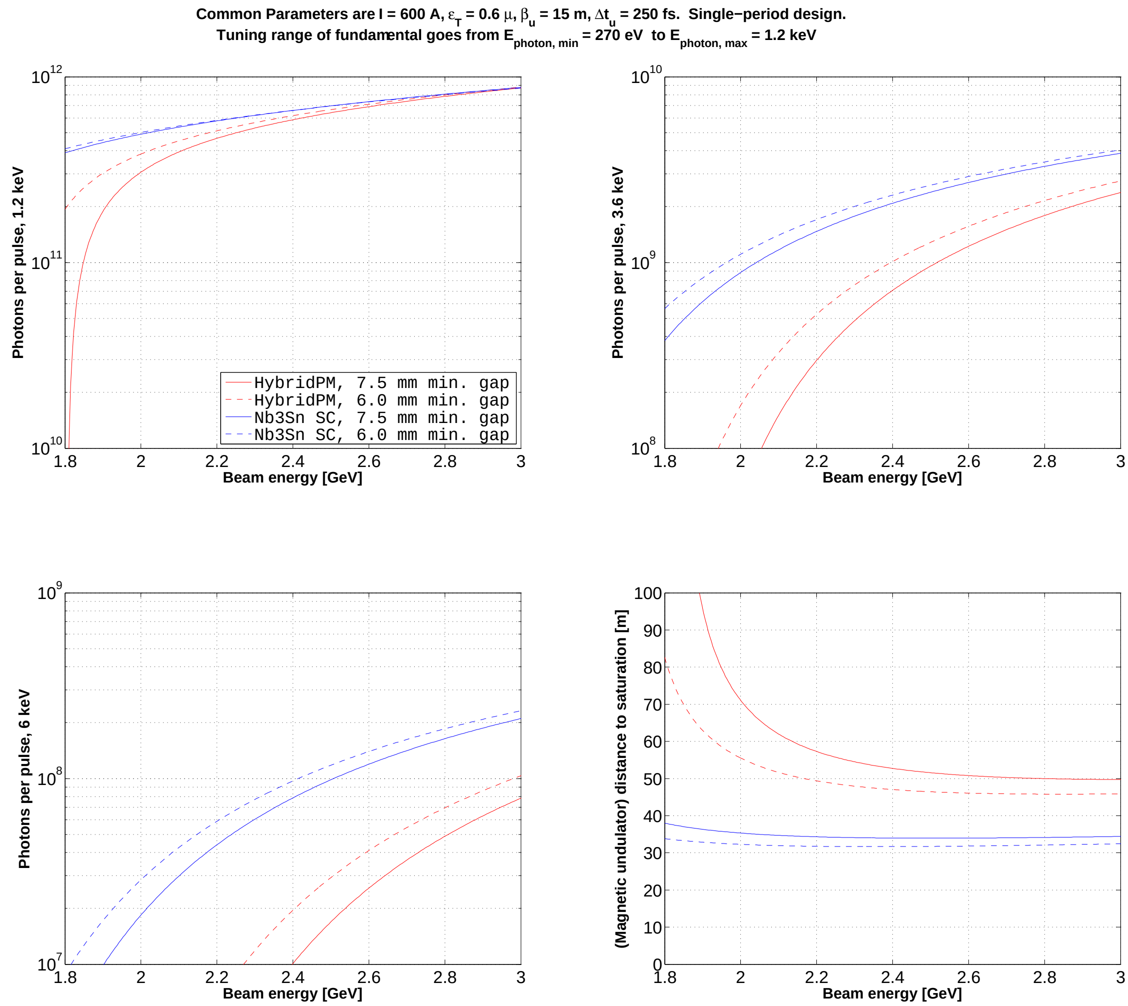

Figure 1: Several performance metrics are plotted as a function of electron beam energy. This is done while holding the tuning range constant. This defines the undulator period as a function of electron beam energy.

use the fitting formula

$$\begin{aligned} B_{\text{peak}}[T] &= (3.469 + 2.96\,\lambda_u[cm] - 0.376\,\lambda_u^2[cm^2]) \\ &* \exp\{(-2.995 - 0.176\,\lambda_u[cm] \\ &+ .072\,\lambda_u^2[cm^2])x\}. \end{aligned} \tag{2}$$

In this formula, the argument of the exponential function is x times a quantity that is nearly constant, so in that sense the functional dependence on x has a familiar form.

Module for estimating saturation power of FEL harmonics

The module that makes estimates for the saturation power of the various odd FEL harmonics is based on literature results, such as those in Ref. [4] and Ref. [5], but also contains original research and novel ways to approximate the production of FEL harmonics. With both shorter gain length and wavelength, it is expected that there will be a minimal effect due to diffraction on the harmonics. The fields are treated as dependent on the local current and bunching of fundamental, so only the local dE/dz matters. In the one-dimensional model, we can assume the radiation is produced by harmonic bunching equal to $b_h \simeq b_1^h$. Three-dimensional effects including higher sensitivity to slippage are included by multiplying some of the Ming Xie parameters by the harmonic number, specifically:

$$f \equiv \left(\frac{b_h}{b_1^h}\right)^2 = \frac{1 + \Lambda(\eta_d, \eta_\epsilon, \eta_\gamma)}{1 + \Lambda(\eta_d, h\eta_\epsilon, h\eta_\gamma)}\,, \tag{3}$$

where Λ is the function from Ref. [3] which characterizes the 3-dimensional effects of the fundamental wavelength of the FEL, according to $L_g = L_{1D}\,[1 + \Lambda(\eta_d, \eta_\epsilon, \eta_\gamma)]$. The nonlinear harmonic power then takes the form

$$\frac{P_h^{NL}}{P_1^{\text{sat}}} = C_h f \left[\frac{J_{(h-1)/2}(h\xi) - J_{(h+1)/2}(h\xi)}{J_0(\xi) - J_1(\xi)}\right]^2 \left(\frac{P_1}{P_1^{\text{sat}}}\right)^h, \tag{4}$$

where $\xi = a_u^2/2(1+a_u^2)$, a_u is the rms undulator parameter, and C_h only depends on harmonic number (for example, $C_3 = 0.094$).

POINT RUNS, SCANS, AND SENSITIVITY STUDIES

A run of STAFF for a single set of input parameters is called a “point run,” and typical output includes the following:

```
Calculations based on the Ming Xie fitting formula
==================================================
All quantities in mks unless otherwise stated.
Input quantities
  beam energy [GeV]             2.400000
  norm transv emit [micron]     0.600000
  current [A]                   600.000
  energy spread [keV]           100.000000
  average beta in und. [m]      15.000000
  undulator period [mm]         29.411765
  output wavelength [nm]        1.000000
Output quantities
  aw_rms                        0.707107
  sigma_x [micron]              43.774935
  rho1D * 1000                  0.585866
  1D gain length [m]            2.306493
  3D gain length [m]            2.895901
  1D sat power [GW]             0.843647
  3D sat power [GW]             0.856284
  3D sat power [MW], 3rd harm 2.592049
  3D sat power [kW], 5th harm 51.921235
  3D sat power [kW], 7th harm 2.692001
  LRayleigh [m]                 24.080244
  etaD                          0.095784
  etaE                          0.246849
  etaG                          0.041061
  Lambda factor                 0.255543

Calculations that use a formula for start-up noise
==================================================
  input power noise [W]         39.567537
  exponential growth over       55.275008 m (mag.)
  The value on the previous line is mag. sat. len.

Calculations that use the rep rate and pulse length
===================================================
  repetition rate [MHz]         1.000000
  t_useful [ps]                 0.250000
  pulse_energy [mJ]             0.107036
  number of photons per pulse 5.388295e+11
  photons/second                5.388295e+17
  number ph./pulse, 3rd harm  5.436951e+08
  photons/second,   3rd harm  5.436951e+14
  number ph./pulse, 5th harm  6.534441e+06
  photons/second,   5th harm  6.534441e+12
  number ph./pulse, 7th harm  2.419973e+05
  photons/second,   7th harm  2.419973e+11
```

In Fig. 1 several performance metrics are plotted as a function of electron beam energy while holding the tuning range constant. This defines the undulator period as a function of electron beam energy. If the plots are done for a lower quality electron beam, for example with an emittance that is 50 % greater, then one is led to consider beam energies such as 2.4 GeV.

STAFF can produce sensitivity studies for any of the input variables. This means that the performance is calculated for a baseline design and for several cases with modified values for an input parameter. For example, in Fig. 2 the performance of a design point is plotted together with several other design points obtained by increasing the transverse emittance by varying amounts.

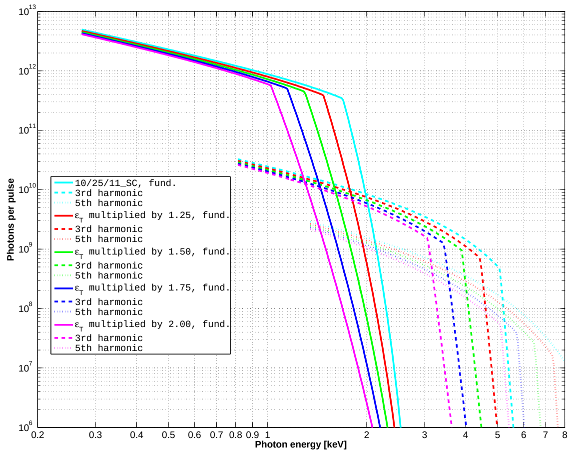

Figure 2: The performance of a design point is plotted together with several other design points obtained by increasing the emittance by varying amounts.

CONCLUSIONS

STAFF enables the user to rapidly explore a large range of Linac and FEL design options. This makes it possible to optimize the integrated system in terms of performance metrics such as photons/pulse, photons/sec and tuning range while ensuring that unrealistic requirements are not put on either the electron beam quality, undulator field/gap requirements or other system elements.

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